Topic: Increasing Light Collection

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Subgroup LoIs:

- "Cost-effective solution for increased light collection in noble-element detectors with metalenses" (contact: Roxanne Guenette <guenette@g.harvard.edu>)
- "Wavelength-shifting reflector foils in liquid Argon neutrino detectors" (contact: Andrzej Szelc <aszelc@ed.ac.uk>)
- "COHERENT: Instrumentation development" (contact: Jing Liu <jing.liu@usd.edu>)
- "Improving large LArTPC performance through the use of photo-ionizing Dopants" (contact: Joseph Zennamo <jaz8600@fnal.gov>)

Executive Summary

The information carried by photons is critical for a wide array of physics measurements in noble element–based detectors, providing a crucial means by which to perform detector triggering as well as position and energy reconstruction and identify interactions of interest. It is essential to fully leverage this information in next-generation measurements, including neutrino interactions from low-energy coherent scattering (CEvNS) up to the GeV energy scale, neutrino astrophysics, and Beyond the Standard Model physics searches such as for low-mass dark matter and neutrinoless double-beta decay. These efforts will require substantial (even as high as 100-fold) increases in light collection, to enable percent or sub-percent level energy resolution, mm-scale position resolution, low-energy detector readout triggering, and/or highly efficient particle identification, including for events at or below 1 MeV energies in detectors at the 100 ton to 10 kton scale. In the context of the broader program in noble element detectors, enhancements to photon collection will lead in general to dramatic improvements in the precision of reconstruction and particle identification, access to a broader range of physics signatures afforded by lower trigger thresholds, and precision timing that will unlock new handles on beam-related events.

Measurement of these light signals, however, presents a major challenge with currently available technologies. For example, in large-scale liquid argon neutrino detectors it is typical to collect <1% of produced photons. This limitation is driven in large detectors by geometric considerations and other active components, total heat load, data volume, and the cost of instrumented surface area. The efficiency of photodetectors and of the wavelength shifters used to convert VUV scintillation light to optical wavelengths for detection also play a role, as do shortcomings of available devices such noise, dark rate, and afterpulsing. In consideration of the massive scale of next-generation experiments — in both run time and target mass — significant research and development is needed to move beyond these limitations and enable the future physics program. While the overall needs are common across a wide range of physics goals, specific measurements will likely require a case-specific optimization of overall photon statistics, timing, and pulse shape discrimination performance. This demands a broad effort to develop a comprehensive and robust simulation of optical photon production, transport, and detection, including characterization of the optical properties of detector materials.

Several promising approaches to improving light collection can address one or more of the limitations noted above, and taken together, provide a set of complementary tools for next-generation experiments: photon collection efficiency may be improved by imaging a large volume on a small active detector surface using lensing, deployment of reflective and wavelength-shifting passive surfaces, enhancements to photon detector and transport efficiency, or the conversion of photons into ionization charge for readout using a TPC. These strategies couple to many other elements of detector design and physics performance, including photon detector technologies, low-energy/low-background physics, simulation tools, and readout and data acquisition R&D. These approaches, implemented individually or in combination as optimized using a detailed microphysical simulation, will afford radical enhancements in the capabilities of future detectors, especially in the challenging low-energy regime near and below

1 MeV. **To increase light collection sufficiently to maximize this compelling future physics program will require a broad approach to R&D funding, to identify and deploy the most successful technologies for each physics context.**

References

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Detailed Summary

Brief Summary

- Light information is essential in noble liquid detectors
  - Triggering
  - Position reconstruction
  - Energy measurement
- Key challenge: Limited photon information in current technologies
  - e.g. Photon collection efficiencies in large-scale neutrino detectors <1%
  - Detector coverage, efficiency, photon production and transport...
- Improvements have broad physics applications
  - Enhanced triggering, position/energy reconstruction → physics sensitivity
  - Low-energy neutrino physics (supernova, solar)
  - Very low energy: dark matter, CEvNS, etc.
- Cross-cutting IF topics include IF2 Photon Detectors
- Improving Light Collection: 4 LoIs
  - Increasing effective photodetector coverage → R. Guenette et al.
  - Improving photodetector & transport efficiency → J. Liu et al.
  - Improving photon transport to photodetectors → A. Szelc et al.
  - Converting photon signal to a charge signal → J. Zennamo et al.

Instrumentation requirements to achieve physics goals

- Overall requirements
  - Increase light detection coverage in large-scale neutrino detectors (currently <1%)
  - Robust wavelength shifting of VUV primary scintillation light
- Requirements for specific measurements
  - Require >40% for percent-level energy resolution at ~1 MeV (DUNE-Beta NLDBD)
  - Light yield >5 pe/keV for CEvNS (COHERENT)
  - e/gamma PID >90% purity at 2 keVee (COHERENT)
  - Track spatial resolution ~1 mm, energy resolution ~5% for ~10 MeV e/gamma tracks (COHERENT)
  - Sub-percent energy resolution for NEXT → 0.5% FWHM at ton scale for NLDBD reach into new param space
  - Time resolution small compared to scintillation time constants

Significant instrumentation challenges

- Practically achievable photosensor coverage is limited in large detectors, by geometry, other active components, heat load, data volume, and cost

- Typical photodetector quantum efficiency is limited to XX
- Photodetector noise, dark rate; afterpulsing (impact on PSD)
- Typical wavelength shifter efficiency is limited to YY
- Scalability to tons to kilotons scale detectors, long multi-year deployment & stability (cf. degradation)
- Optimization of photon statistics, timing, PSD
- Robust simulation, characterization of optical properties

Instrumentation developments

- Increase effective photodetector coverage using focusing → R. Guenette et al.
- Improve photodetector & transport efficiency → J. Liu et al.
- Improve photon transport to photodetectors with WLS foils → A. Szelc et al.
- Convert photon signal to a charge signal with photoionizing dopants → J. Zennamo et al.

Relevant physics areas

- Enhancements in:
    - Better energy reconstruction
    - Triggering
    - Position reconstruction
    - PSD
    - Timing resolution. Hadron spectroscopy (time evolution of nu flux). Stopped pi sources.
- Low-energy neutrino physics (supernova, solar neutrinos)
- Very low energy (dark matter including accelerator-produced low-mass DM, CEvNS, etc.)
- MeV scale NLDBD, scalable
- CEvNS at reactors
- Improvements in GeV-scale measurements

Relevant cross-connections (e.g., other topical groups, other white papers)

- IF, especially IF2: Photon detectors
    - Fast photon detectors — Beam timing? Optical TPC, etc.
- NF, especially NF10: Neutrino detectors
- DUNE low-energy physics program “LEPLAr” program + whitepaper
    - DUNE low background module WP
- Simulations e.g. NEST, event generators for low-E e.g. MARLEY
- DAQ/triggering/data volume/zero suppression, on-detector zero suppression & DAQ. QPix, Klein ASIC
- A. Mastbaum, F. Psihas, J. Zennamo, “DUNE- β”, Snowmass 2021 LOI (NF5, NF10).

Further reading (e.g., reference for existing TDR, reference paper, etc.)

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